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COPATH—A SPREADSHEET MODEL FOR THE ESTIMATION OF CARBON FLOWS ASSOCIATED WITH THE USE OF FOREST RESOURCES*

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Abstract—The forest sector plays a key role in the global climate change process. A significant amount of net greenhouse gas emissions emanate from landuse changes, and the sector offers a unique opportunity to sequester carbon in vegetation, detritus, soils and forest products. However, the estimates of carbon flows associated with the use of forest resources have been quite imprecise. This paper describes a methodological framework—COPATH—which is a spreadsheet model for estimating carbon emissions and sequestration from deforestation and harvesting of forests. The model has two parts, the first estimates carbon stocks, emissions and uptake in the base year, while the second part forecasts future emissions and the uptake under various scenarios. The forecast module is structured after the main modes of forest conversion, i.e. agriculture, pasture, forest harvesting and other land uses. The model can be used by countries which may not possess an abundance of pertinent data, and allows for the use of forest inventory data to estimate carbon stocks. The choice of the most likely scenario procides the country with a carbon flux profile necessary to formulate GHG mitigation strategies.

1. BACKGROUND

The importance of forestry to global climate change has significantly increased as more light has been shed on the magnitude of greenhouse gas (GHG) emissions from forestry as well as the potential for using forests to sequester carbon dioxide (CO_2) from the atmosphere. Estimates of global GHG emissions from different sectors indicate that by the end of the last decade, conversion of tropical forests to other land uses contributed about a fifth of the anthropogenic CO_2 emissions.[1] Most of the forestry-related emissions originate from the tropical biome, since it is estimated that the other biomes (temperate, boreal and sub-arctic) are either in biomass equilibrium, or provide a small sink for atmospheric carbon.[2,3,4] The potential for mitigative effects through conservation and reforestation has further heightened the need to better understand the dynamics of tropical forestry and its implications to global climate change.

Although there is a broad agreement on the general interplay between greenhouse gases in the atmosphere and climate, there is more uncertainty about the quantities of greenhouse gases released from the use of forest resources, especially from tropical deforestation and degradation. Similar uncertainty exists with regard to the amount of carbon sequestered by forests, forest soils and forest products. Overlaying the two areas, more uncertainty surrounds the extent of the impact of both CO_2 fertilization and climatic change on plant growth, migration and feedback into the carbon cycle. The main reason for this uncertainty is the lack of precise data on the constituent variables required for the estimation. Such information includes classification of vegetation ecosystems, biomass density, the rate of change of the biomass density through growth and removals, the amount and capacity of edaphic storage and release of greenhouse gases, and the extent of storage and release through forest products.

The estimates of carbon emissions from deforestation in the Tropics have varied widely, a fact which can be confirmed by a quick glance at the estimates of the extent and rates of deforestation by various researchers during the 1980s. Myers,[5] estimated that the tropical forest biome was losing about 200,000 km^2 annually, of which about half was considered to be totally destroyed, and the other half was expected to undergo partial recovery after being used for shifting agriculture. FAO/UNEP[6,7,8] reports give

*COPATH was developed by the authors at the Lawrence Berkeley Laboratory, and has been used by F-7 network researchers to estimate carbon flows in their respective countries. The model is in the public domain, and is available on diskettes upon request. This work was supported by US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division.

Table 1. Carbon fluxes of low latitudes

Author	Carbon flux (Gt)
Seiler *et al.*[21]	0.4–1.2
Molofsky *et al.*[22]	0.6–1.1
Houghton *et al.*[15,16]	0.9–2.5
Detwiler & Hall[23]	0.4–1.6
Hao *et al.*[24]	0.9–2.5
Myers[17]	0.4–1.4
Makundi *et al.*[25]	1.1–1.7
FAO[26]	1.3*
Dixon *et al*	1.2–2.1

*Does not include emissions from below-ground organic carbon.

an estimate of 73,000 km^2 of tropical forests annually being converted to other land uses. Melillo *et al.*[9] and Molofsky *et al.*[10] showed that definitional and classificational discrepancies were partially responsible for the different estimates. In 1988, FAO claimed that there was little evidence of accelerated deforestation,[11] while other researchers such as Myers,[12,13,14] and Houghton *et al.*[15,16] were arguing that the rate was increasing. Myers[17] estimated that the tropical deforestation had increased to 142,000 km^2 per year, for example, whereas Myers estimated that Brazil was loosing 50,000 km^2 per year by 1989. A Brazilian Space Research Agency report (INPE/IBAMA) estimated losses of 25,000 km^2 per year.[18] Such differences indicate a critical lack of reliable data on the major aspects involved in deforestation and associated carbon flows.

The methodology and the underlying assumptions used to generate the estimates also produced sharply different results. The INPE (1990) report gives two figures for deforestation in the Brazilian Amazon, i.e. 17,000 and 25,000 km^2 per year depending on the set of assumptions one prefers to use on pre-1978 historical deforestation rates for Brazil. Mahar,[19] in two different reports, provides estimates of 48,000 and 80,000 km^2 per year for the same Brazilian Amazon deforestation based on a report by Setzer *et al.*[20] to INPE on total area burnt in 1988. Although the five-fold discrepancies are not the norm in the tropical countries, studies have produced significantly different estimates for most countries.

The variation in estimates of rates of deforestation, together with the imprecision in the estimates of the other variables, have led to different estimates of consequent carbon stocks and flux. For example, the carbon flux from tropical forestry (Gt), as estimated by various researchers, shows a wide variation (Table 1).

By comparing the results of several studies, Detwiler and Hall[23] found that the carbon release estimates vary significantly depending on the method of biomass data collection. A low estimate of 0.42 Gt of carbon release based on inventory volume data was obtained, compared to a high of 1.55 Gt based on destructive sampling data. In their own simulation, the estimate for carbon flux based on volume was 36% lower than that based on destructive sampling. Although more recent estimates, such as Myer's for 1989, show a closer range, i.e. 2.0–2.8 Gt, the basis for the uncertainty remain unchanged. Houghton[28] gives an estimate of 1.1–3.6 Gt of carbon flux a year depending on the estimates of conversion of tropical forest to other land uses.

In the early 1990s, various efforts were launched in an attempt to improve the estimates of deforestation and carbon emissions, especially in the most active tropical forests. A recent study[27] using latitudinal classification of the world's ecosystems gives a deforestation estimate of 154,000 km^2 per year for the low latitudes (0–25°) for the period 1971–1990, with a corresponding carbon emissions estimated at 1.6 Gt. FAO's 1990 forest resources assessment also gave an estimate of 154,114 km^2 of annual deforestation for the period 1981–1990 [26] with an estimated loss of 1.3 Gt of above-ground carbon. Although these estimates are not directly comparable to the past estimates, they give an indication that the global estimates are beginning to converge. Similar convergence has also been demonstrated for estimates of deforestation and emissions from the Brazilian Amazon.[25,29–31] Despite these efforts, the lack of reliable country-specific data combined with the use of different assumptions and methodologies, as well as an inadequate understanding of the dynamics of the deforestation process in the Tropics leaves the estimates wanting, especially at the individual country level.

One of the efforts to improve the precision of estimates was proposed at the IPCC meeting in Sao Paulo in 1990. This approach was to focus on individual country estimation by using a network of scientists resident in the main deforesting countries who would use a common framework to estimate land-use changes and the corresponding GHG flows for each one of the countries.[32] In the process, areas of severe data deficiency would be identified and efforts would be made to generate more accurate data in these areas. On these grounds, the model described in this paper was developed as a common tool to

Figure 1
The Modular Structure of COPATH

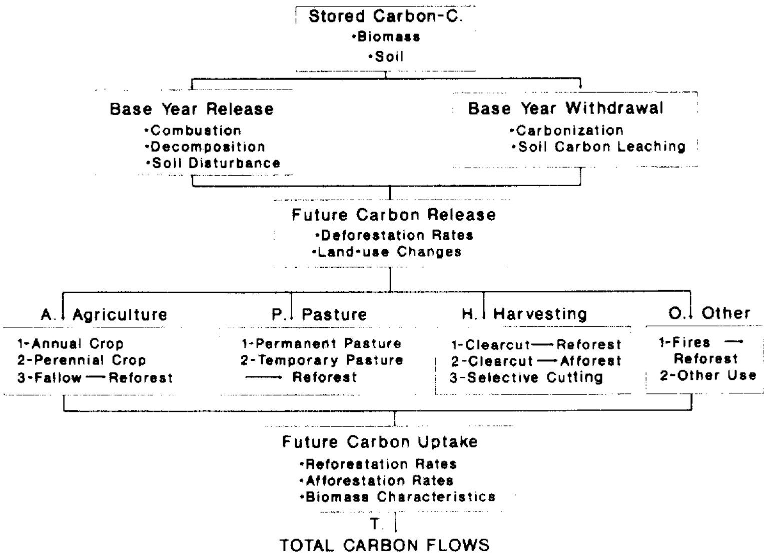

Fig 1

assist the scientists in the respective countries to undertake the estimation for those individual countries.

The model has been applied in estimating carbon flows from deforestation and forest resource use in the F-7 countries,* and it is currently being used by a number of countries involved in the U.S.- supported country studies initiative. The results from the F-7 countries give an emission estimate of 0.87 GtC for 1990, which when extrapolated to cover the tropical biome yields an estimate between 1.1 and 1.7 GtC, with a working average of 1.4 GtC per year for the late 1980s and early 1990s.[33] The individual countries' results are expected to be a useful input in the national climate change policy-formulation process. These policies may be critical to the sustainable management of a county's forest resources.

2. STRUCTURE OF COPATH

2.1. *General description*

The model described here is a framework for calculating carbon emissions and sequestration based on inter-connected spreadsheets. It is designed for use in either the SYMPHONY or LOTUS 1-2-3 computer programs, and can be run on any PC or compatible computer with at least an 80286 (or equivalent) microprocessor. Using the lowest computing capability allows for the wider use of the framework in a region which is not awash with the latest computing technology. On the other hand, the need for wide application leads to a Random Access Memory (RAM) constraint, which partially dictated the current structure of the model. COPATH borrows its name from the initials of the constituent modules upon which the interconnected spreadsheets are based (Fig. 1).

The model is divided into two main parts—BASIS and FORECAST. The first part takes specific information about the forest and computes stored carbon, emissions and sequestration for a desired base year. The second part takes the base year estimates and by applying various assumptions on the future states of the forest resource and consumption of forest products, it forecasts the extent of future carbon emissions and uptake from the forest sector. Four major conversion modes are accounted for in this framework.

FORECAST is subdivided into four modules which undertake the computation for each major mode of deforestation, i.e conversion to agriculture (AGRIC); conversion to grazing land (PASTURE); various management regimes guiding forest harvesting policy (HARVEST); and other land uses such as dams, roads, mining, re-conversion of non-forest land to

*The countries involved in the F-7 research network on tropical forestry and global climate change are Brazil, China, India, Indonesia, Malaysia, Mexico, Nigeria, Tanzania and Thailand.

forests, forest fires, and human settlements, etc. (OTHER). The totals for each module are extracted and summed to obtain the emissions and uptake for any given forest type (life zone). The process is repeated for each life zone and then added up for the country as a whole. A biome-wide aggregation can then be obtained from these individual country estimates, provided that the level of imprecision in each estimate is comparable.

2.2. *Description of BASIS*

This portion of the program computes carbon emissions and uptake for the base year, consequent from existing policies regarding the use of the forest estate. In future versions of the model, current emissions from past deforestation, and sequestration by non-mature growing stock will be included to account for the carbon implications of past forest land-use policies.

The forest in a given country is classified into various life zones such as the Hodridge[34] classification which includes at least 9 zones found in the Tropics. In most cases, the forest area is already classified into general life zones. Vegetation maps as constructed from both remote sensing sources and ground truthing are the basic tools in classifying the life zones. Satellite imaging is used to continuously monitor the state of the vegetation in many of the major forested countries of the world. The use of similar life zone classifications for each country helps to increase the consistency of the estimates and makes zonal comparison and global aggregation possible.

In most countries, the life zones will breakdown into a few 'true' forests including montane, submontane, transitional and lowland types, swamp and terra-firma types, evergreen, semi-deciduous, equatorial and human-grown plantations. In some countries where locally unique ecosystems such as mangrove forests and man-made plantations cover significant areas, they will be treated as separate life zones for the purpose of this exercise. If a life zone is not geographically contiguous, or lies in more than one administrative unit of separate record-keeping with respect to land use, then the estimation may need to be repeated for the respective life zone in each administrative unit.

2.2.1. *Determination of stored carbon.* For each of the identified forest types, we want to find out the total amount of carbon stored up to and including the base year, in this case 1990. Any flux due to the use of forest land is therefore a measure of changes in this stock of carbon. The total stored carbon for the portion of the forest with destructive sampling data is computed by multiplying the dry biomass density by the carbon content of the dominant species, or a weighted average of the most common species in the representative area. It is imperative to point out that the use of area-weighted average biomass leads to biased estimates of carbon release as long as we use incomplete life zone classification while certain life zones are disproportionately preferred for various land uses such as agriculture or pasture.[35] Destructive sampling data are very scanty and tend to be concentrated in a few medium moist life zones.[36]

The most commonly available data are from inventory sampling of the above-ground stem biomass. For the remainder of the forest area, inventory data deductive methods following Brown and Lugo,[36,37] Brown *et al.*,[38] Detwiler *et al.*[35,39,23] and FAO[26] will be used to estimate the total biomass and hence the total stored carbon in the vegetation for each life zone.

2.2.1.1. *Stored carbon in the vegetation.* The following is a list of items required as input to the BASIS part of the model for computation of stored carbon in the vegetation by using the inventory sampling approach.

(i) Total area (ha) covered by forest type i in base year t.

(ii) Dominant species covering forest type i. This is required to compliment other species-specific data such as density, basal area, etc. If the species information is not sufficiently available, then the inventory and other information will be based on a weighted average of the known species' structure.

(iii) Inventory (m^3/ha). The estimate of stemwood volume or merchantable timber provides a basis for estimating the total aboveground biomass. The volume is relatively stable for mature forests.

(iv) Wood density (t/m^3). The average wood density for the stem will be used to calculate the total biomass of the forest. If unavailable, then wood density for the dominant species should be used. In many cases, the data on wood density exist for oven-dry wood of specified humidity for many commercial species.

(v) Stemwood wet biomass (t/ha). This is the product of inventory and wet wood-density as given above.

(vi) Ratio of stem to total wet biomass above ground. Each forest type has a different ratio of stem to total biomass above ground due to the species composition and the plants' physiological characteristics. These data are obtained from destructive sampling methods which involve measuring the biomass of the respective flora above the ground.

(vii) Ratio of above-ground to subterranean biomass. The amount of biomass in the roots varies a great deal depending on the species' rooting systems and on-site pedological properties. This information is also obtained from destructive sampling studies. Very few studies have been done for specific ecosystems and as such, the use of some average ratios from the few studies may be necessary.

(viii) Ratio of wet to dry biomass. This is used for converting the wet biomass to a dry biomass estimate.

(ix) Carbon content of the dry biomass. This differs significantly among species, and small errors in this variable can lead to large errors in the estimate of carbon stock. emissions and sequestration. In the absence of this information, researchers have used 0.50 tC per tonne of dry biomass.

By applying the four ratios to the stem wet biomass computed above, and then multiplying by the area (ha) covered by forest type in the base-year, we obtain the total amount of stored carbon for a given life zone up to the year of analysis. For mature forests, this amount is stable and does not change substantially unless destructive factors such as fire, insects and vermin, or human activity interfere with the vegetation ecosystem. The total amount of stored carbon represents the maximum carbon which can be released into the atmosphere from the vegetation if and when deforestation takes place. Some significant amount of carbon stored in the soil will also be released during the conversion.

2.2.1.2. *Soil carbon.* Soil organic carbon constitutes a major pool of emitable carbon in the forest sector. Deforestation reduces soil carbon content mainly through enhanced oxidation and erosion of the top soil. The estimate of soil carbon in forest ecosystems is very uncertain, and the few estimates of soil carbon in tropical forests show a very wide variation. Detwiler[39] estimates that tropical soils contain between 52 and 67 tC per ha and that up to 40% is released within 5 years of clearing, depending on the subsequent land use. Other studies have shown a wider variation depending on the life zones covered and the depth of the profile used for the estimate. Pedological and soil chemistry studies are good sources of data for soil carbon content. If these data are unavailable for a given life zone, then estimates can be made based on zonal or national cross-sectional studies and then adjusted for pertinent local variates.

2.2.2. *Determination of released carbon.* Past studies have used the term "deforestation" to describe a wide range of forest-clearing activities. In this model, we use consistent definitions and identify the key variables necessary to undertake a sound estimate of carbon flux from changes in forest cover. For the purpose of estimating CO_2 emissions, any activity resulting in a change in the amount of carbon stored in a forest should be included. The model focuses on two major categories of forest conversion which have an estimable effect on carbon flows, i.e. deforestation and logging.

Deforestation refers to the transformation of forest lands into other land uses. This would include the clearing of forest vegetation for the purpose of annual and perennial agriculture, be it permanent or fallow, as well as the conversion of forest areas to pastures. Also under this category is the harvesting of forests by clear-cutting methods which results in a long-term loss of tree cover from the area. Finally, we include all other activities which result in significant loss of forest cover such as the construction of dams, mining, human settlements, communications routes, and destruction by anthropogenic forest fires. For the purpose of carbon flows, forest degradation is treated as partial deforestation.

Logging refers to conversion activities in which only a fraction of the trees are removed from the forest, as is the case for most selective-harvesting activities. Clear cutting, if followed by replanting, also falls under the term logging.* Harvesting wood products which are replenished in a year or so, e.g. branches and figs for firewood or poles and withies for construction is not considered as logging.

When deforestation takes place, carbon is released in two stages. During the conversion year, some will be released through combustion and/or soil disturbance. In this version of the

*The degree to which the biomass is affected by logging activities varies considerably from place to place.

model, we are allocating all the soil carbon release to the year of conversion. In future versions, the soil carbon for each land use category will be released over the appropriate number of years. However, given the magnitude of the sector and the long-term nature of these estimates, and considering the lack of reliable information on tropical forest soil-carbon release processes, the assumed allocation would not significantly affect the robustness of the carbon flow estimates.

The remainder of the biomass-based carbon is released over a period of time, mainly through decomposition and oxidation. The amount of carbon released in each of the two stages depends on the mode of forest conversion and the type of use the biomass is put to. Forest products have different lifetimes which also vary with the location and condition of use. Construction timber could last as few as 10 years in moist tropical areas, while lasting 30 or more years in an arid environment. Whereas newsprint may decay in 1–2 years, it may take 50–100 years or more for treated structural wood to oxidize. To simplify the analysis, forest products are divided into short- and long-term products. The model allows for specifying various lengths of time for these two types of products depending on the actual product and expected condition of use. For example, whereas woodfuel is a short-term product which may last only 1 year, paper is a short-term product which may last for 5 years.

In order to accommodate these variations, the emissions from each land use conversion activity are computed separately. If more than one method is active for a given area, the emissions from each method will be proportionately summed from the respective activities. All the four main land use conversion modes have both prompt and residual release of carbon into the atmosphere. In this model, the sum of emissions from combustion and decomposition of biomass cleared in the current year, together with emissions from soil disturbance is referred to as prompt release. The rest of the delayed carbon release will be from annual decomposition, while the sequestered carbon is referred to as annual CO_2 uptake.

The treatment of emissions which are delayed over time increases the complexity of the estimation. For the base year, i.e. the current year of emissions estimation, the amount of carbon dioxide released into the atmosphere due to land use conversion in the past years will depend on the precision of our knowledge of the extent of deforestation in each of the past relevant years. In the ideal case, the emissions carried forward from the past will be the sum of all emissions expected to be released at time t from each of the preceding years which had a deforestation or forest utilization activity. Given the fact that our data on historical rates of deforestation and the relevant carbon stocks are inadequate, we need to use an approximation of the emissions carried forward from the past. In a case of a constant rate of change of land use, the historical emissions will approximately equal future emissions if the structure of forest product use with respect to duration of product use remains the same.

Different forest types and conversion activities may require different approximations due to the apposite variations which affect release. The residual release from the current year's vegetation removal will be distributed to future years, depending on the release processes. In each conversion method which involves burning, a determination of the proportion of the biomass which is carbonized has to be undertaken due to the long carbon retention period involved. Field charcoal is estimated to withdraw carbon from this cycle for many centuries. The prompt and annual release described below is for the non-carbonized proportion of the biomass.

2.2.2.1. *Agriculture*. Three types of forest conversion to agriculture are considered in this model. Conversion to permanent agriculture is subdivided into annual and perennial crop lands. The area used for fallow agriculture is assumed to be used for annual crops only.

The method of conversion determines the amount and distribution of release. More soil carbon will be released in the annual crop than in the perennial crop cycle, and everything else being equal, the length of decomposition will be longer for the perennial crop area. Different areas employ varying levels of burning, depending on the forest type, expected crop husbandry, duration of fallow, etc. On one extreme, the land is cleared and the biomass piled in bundles and left to rot, while in some dry areas, most of the vegetation is burnt with very little left for decomposition. We can use some average estimates of proportion released through combustion, decomposition and soil disturbance in the cases where no studies of release processes have been done.

2.2.2.2. *Pasture land.* Two types of conversion to grazing land are recognized in this model, i.e permanent and fallow grazing land. In the first type, the forest is cleared and used for pasture as a permanent land use, whereas in the latter case, the area is abandoned after being used for a given period due to any number of reasons. The prompt and residual release of carbon dioxide will be treated exactly the same as in the case of agricultural conversion. The difference is that the distributions of release from combustion, decomposition and soil disturbance will differ due to the kind of activity being undertaken on the land.

2.2.2.3. *Harvesting and wood utilization.* In this model, three harvesting regimes are recognized to have different carbon flow effects. They consist of clear-cutting followed by natural regeneration, clear-cutting followed by afforestation with man-made plantations, and selective cutting with natural reforestation. Each is further analyzed with respect to the intended use of the harvest, i.e logging for short-term wood use such as pulp, paper and woodfuel; or for long-term wood use such as timber extraction for structural wood.

The area being logged is assumed to have no prompt release due to combustion, and the biomass which may be used for wood fuel will appear under release from short-term product use. The prompt release in this case will be from soil disturbance and possible current year decomposition. The delayed release will come from both the decomposition of biomass left on the field and from oxidation of the wood in use. With the knowledge of the rate of growth of consumption of wood for long-term use, we compute the amount of release in year t from oxidation of wood in long-term use. Although the oxidation is residual, in this model we make a simplifying assumption that all the wood in long-term use will release its carbon at the beginning of the defined long-term period. Given the smooth nature of the wood product consumption curve, the lump-sum release assumption is not significantly distortive. To the extent that one knows the oxidation process for a given wood product end-use, the use of the appropriate decay function would reduce this apparent distortion.

The release from short-term wood use is assumed to be equally distributed over the length of the short-term period. Various product types may be classified into different short terms depending on their specific length of use. Woodfuels and newsprint may be considered to be very short term, with an average life span of 3 years, while paper and paperboard may last for 10 years. Harvesting for exports is not treated any differently from that portion used for domestic consumption. The exported timber would be assumed destined for its historical use in the importing country, and the oxidation is tracked as if the wood was used in domestic consumption. Although this assumption helps to track all emissions from a given forest use, it does not address the crucial issue of assigning responsibility for the carbon emissions between the wood exporter and importer. If it is necessary, the proportion of emissions from exported products should be subtracted from the prompt emission estimate.

2.2.2.4. *Other land uses and forest fires.* This mode of deforestation will include the areas used for dams and reservoirs, communications lines such as roads and railways, mining and human habitation such as permanent villages, towns and other physical facilities. Also included here are those areas from all the other modes which become permanently denuded, with little or no regrowth of vegetation.

The prompt release from other land uses is a sum of soil carbon release and a proportion of the biomass which may be used immediately or combusted. This varies depending on the specific land use. The proportion left behind is assigned to future decomposition. In some cases such as dams, a great deal of the stored carbon is trapped for many years. Each case has to be treated on its own merits.

Crown forest fires which burn a significant portion of the woody vegetation release large amounts of CO_2 whenever they happen. The proportion which is carbonized is withdrawn from the carbon cycle for a long time. Some researchers estimate that the charcoal is not oxidized for up to 1000 years.[40] However, consequent fires may lead to the smoldering of part or all of the previously carbonized biomass. Forest fires also release other greenhouse gases such as nitrous oxide. The area which is burned and the proportion of the woody vegetation which is affected is estimated in this mode. The non-woody vegetation which will regrow in a period of a year or so is not considered as a source of net carbon emission in this case. However, this portion is essential if one is estimating emissions of the other relevant greenhouse gases such as methane and nitrous oxide. If one of the other conversion activities such as harvesting is also affected by forest fires, a downward adjustment will need to be done on the released carbon.

It should be noted that other GHGs are released during deforestation and forest resource use. These trace gases include methane (CH_4), nitrous oxide (N_2O), oxides of nitrogen (NO_x, i.e NO and NO_2), carbon monoxide (CO) and other non-methane hydrocarbons (NMHC). These are largely emitted during biomass combustion, but also in enteric fermentation by ruminants and termites, and through anaerobic fermentation in flooded areas such as hydroelectric dams and in ruminants. The current version of the model described here does not explicitly include the estimation of these trace gases, but following Andreae *et al.*[41] and Crutzen and Andreae,[42] one can apply compound ratios to the total carbon release as estimated from COPATH to obtain an estimate of the associated trace gas emissions.[43] These ratios are also given for various types of biomass fuel in estimating methane emission from biomass combustion.

Future versions of the model will include estimation of trace gas flows in the forest sector.

2.2.3. *Determination of carbon uptake*. The amount of carbon sequestered after clearing a forest of vegetation and converting the area to another land use depends on the type of vegetation which replaces the primary tropical forest. Research is still under way to find out the extent to which an increased concentration of atmospheric carbon may influence sequestration from its possible effects on plant growth.[44] Such CO_2 fertilization has been shown to occur in greenhouses, evidence of increased biomass accumulation in the field is still being sought. In this model, we assume that the growth of the subsequent vegetation is not influenced by the increase in atmospheric CO_2 concentration, and if evidence exists to that effect, this influence will be captured in the relevant estimates of net long-term primary productivity used in estimating carbon uptake. In this model, the computation of carbon sequestration for each mode of land use conversion will be done separately.

2.2.3.1. *Agriculture*. If the forest is converted into permanent agricultural land, then the uptake will depend on the kind of agricultural crop introduced. A long-term woody crop such as rubber, coffee, cocoa, fruit trees, etc. will be considered in some way to be similar to a tree crop and will (may) have a net uptake potential. In this case, the computation of CO_2 uptake will require data on the crops biomass dynamics and its husbandry. The carbon emissions and uptake for perennial agricultural crops after maturity will not be addressed in this model. Together with the land for permanent annual crops, this land will be left to the agricultural sector for the purposes of GHG flow estimates. In any case, conversion to a non-woody annual crop leads to negligible net carbon uptake, if any.

If the land is converted to a swiddening type of farming, where after a number of years it is left fallow and reclaimed by natural secondary vegetation, then the computation of CO_2 uptake will be handled like the case of natural regeneration after the fallow period. In this case, we will need to use growth/yield studies to compute the change in biomass every year up to maturity of the secondary forest. A linear growth approximation may be adequate if we know the biological rotation age of the forest. In this program, we use a linear growth curve because the deforestation and the subsequent land use is a continuous process, and as such, summation of annual sigmoid growth curves over a rotation yields a linear growth approximation for the forest.

Estimates of the mean annual increment (MAI) and carbon content of the ensuing vegetation can be obtained from studies of the neighbouring secondary forest from past deforestation. In the absence of these data, adjusted biomass data for the outgoing primary forest can be used as a basis for the carbon uptake computation. If the MAI is given in terms of volume per unit area, it has to be converted to weight per unit area using the average wood density of the secondary vegetation. The carbon uptake per unit area is the product of the MAI in t/ha and the carbon content of the secondary forest, multiplied by the stemwood-to-aboveground-biomass ratio, and the total-to-aboveground-biomass ratio as done in Section 2.2.1.1 on carbon storage. Where direct estimates of net primary productivity (NPP) of the new land use are known, these provide a more accurate estimate of carbon sequestration.

2.2.3.2. *Pasture land*. For permanent pasture, the uptake potential is very small due to lack of woody vegetation. Any uptake resulting from growth of forage grasses will not be covered in this model. This can best be addressed within the livestock sector. The uptake to be covered in this model comes from regrowth of abandoned or fallow pastures.

The speed and extent to which an abandoned pasture gets reclaimed by a natural forest differs depending on the pasture management regime preceding the abandonment.[45] To the contrary, there is evidence that some vulnerable ecosystems are so modified by land use practices and nutrient loss that their regeneration never achieves the biomass level prior to the deforestation.[46,47] The computation of carbon uptake by the regrowth will be done in the same way that fallow agriculture was handled above.

2.2.3.3. *Harvesting and subsequent management regimes*. The three harvest/management regimes discussed above have different carbon uptake streams. In the selective cutting case, we are assuming a natural regeneration of the biomass proportional to the amount removed. The uptake potential is therefore proportional to the extent of re-thickening of the forest.

In the case of clear-cutting followed by natural regeneration, the computation of CO_2 uptake takes the growth-curve approach mentioned earlier. The third option is to replant the area with either new or the same species but in a plantation format, in most cases as monocultural vegetation. The CO_2 uptake ramifications of afforestation are enormous because of the potential to amass a lot of biomass per unit area. Despite the larger biomass, the approach for computing uptake is essentially the same as for reforestation.

2.2.3.4. *Other land uses and forest fires*. The CO_2 uptake of fire-scorched areas is dependent on the frequency of the fires and the type of destruction caused. For annual fire areas, there is very little net uptake due to the type of vegetation burned. If it is a one-time crown fire, the uptake implications are very similar to selective harvesting or clear-cutting and the options available for CO_2 uptake are the same. The emphasis is on fires which are caused or influenced by human activities. In the forest fire case, we equate the regeneration to a partial reforestation by a similar forest type. The activities included in other land uses do not provide for a new woody vegetation, and as such the CO_2 uptake is minimal. Permanently denuded lands from other conversion modes are a typical example.

2.2.3.5. *Soil carbon uptake*. In each of the four conversion modes, the soil carbon replenishment is treated in the same way. The NPP estimate should include the rate at which the soil carbon is being replenished after the conversion of the area. In the absence of these data, we assume that the soil carbon will be replenished over the lifetime of the new vegetation, and the new equilibrium will approximately be the same as the soil carbon before the conversion. To the extent that this assumption holds, the amount of soil carbon lost in the conversion will be regained, and the annual distribution can be assumed to mimic the vegetation growth pattern. Under different silvicultural and crop husbandry conditions, the new soil carbon may be less than or exceed the prior equilibrium. Very few data exist about the dynamics of soil carbon replenishment in different land use conversion modes.

Using the above described BASIS module, the base year estimates of stored carbon, release and uptake are estimated for each forest type in the country and then aggregated to obtain the stock and flux from the country's forest sector. These estimates are used as inputs in the forecasting of future emissions and sequestration. In the following section, we present the models and assumptions underlying the FORECAST portion of the program.

3. DESCRIPTION OF FORECAST

In this version of the model, sequestration by growing forests from past regeneration and afforestation as well as emissions from past deforestation and forest use are not being accounted for. This is due to our present emphasis on carbon implications of present and future policies on forest resource utilization. With knowledge of past deforestation and resultant land uses, it should, however, not be difficult to incorporate the historical emissions and uptake into this analysis.

The net CO_2 release is the sum of prompt release and emissions from annual decomposition, less the amount sequestered in the year under consideration. The prompt release mainly comes from combustion and soil disturbance. We assume that the soil carbon is released in the year of deforestation. Any initial decomposition of light biomass such as leaves, bark, etc. is also included in the prompt release estimate. The residual biomass which is not carbonized is assumed to decompose over a known period of time, and we assume equal release every year. The annual decomposition is therefore a cumulative amount from all past years due for release in year t. We assume that decomposition begins in year $t + 1$. The CO_2 uptake is assumed to begin in the base year and as described in the BASIS section, the uptake is derived from an assumed linear growth curve for the new crop. Use of yield curves or NPP functions will yield a more accurate uptake trend, but we feel that the status of data availability in the biome justify the use of the simpler function.

The estimate of future net release is based on knowledge of deforestation in the base year, the decomposition period, the rate of growth of secondary vegetation, the rotation age and the change in the rate of deforestation. If such estimates for future deforestation rates exist, they are used as direct inputs in the FORECAST module. In the absence of such estimates, the model assumes that due to the exhaustability of the forest resource, political pressure and environmental compulsion, although the rate of deforestation will continue increasing commensurate with the growth of the deforestation pressures such as rural population, it will begin to decline as the counter-pressures assert themselves. The rate of increase and decline, including the turning point, will be estimated by the researcher based on information exogenous to this model. For example, in the absence of any other estimate of rate of land use change, one can assume that the deforestation will increase at a decreasing rate, until the country reaches a point of sustainable forest management, as is now thought to be the case in many temperate countries.

3.1. *Structure of the forecasting model*

3.1.1. *Net carbon release in year t*. The release and uptake for the base year is used to forecast future emissions. In general, the net carbon release for the country from all forest types in year t can be represented as:

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} [R_{it} + d_{it} - u_{it}],$$

where i = forest type, n = number of forest types in the country, t = year of estimation, N = net carbon release, R = prompt release from combustion and/or soil disturbance, d = amount released from decomposition, and u = carbon uptake.

3.1.2. *Future annual estimates*. The representation of the model can be simplified by describing the process in three various periods in the future, i.e (i) base year–decomposition length, (ii) decomposition length–biological rotation age and (iii) beyond the rotation age of the new crop. In this model, we are assuming that the rate of deforestation will be changing as a known proportion of the base year deforestation levels, and as such, the prompt release, decomposition and uptake will follow similar behavior subject to the specific modes of uptake and release.

3.1.2.1. *Period between base year and length of decomposition*. During this period, the annual decomposition increases every year due to the residual emissions brought forward from previous years. Given the assumptions we used regarding the change in deforestation rate, the maximum net carbon release per year will be achieved during this period when p goes to zero. The net emissions for year t can be approximated by the following equation.

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} \left[r_i^{\alpha-1} R_{i0} + \frac{1 - r_i^{\alpha-1}}{1 - r_i} (d_{i0} - u_{i0}) \right],$$

where p = percent change in deforestation from year $t-1$, $r = 1 + p$, $\alpha = t - t_0$ = number of years since the base year, R_0 = carbon release during the base year, d_0 = initial annual carbon release from decomposition, and u_0 = initial annual carbon uptake.

3.1.2.2. *Period between length of decomposition and biological rotation*. In this period, the annual decomposition is the sum of emissions from the past β years. The prompt release and uptake terms are the same as in the period between the base year and the length of decomposition. It is during this period when net uptake starts to exceed release in the relevant modes of land use conversion. The net release can be represented as:

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} \left[r_i^{\alpha-1} R_{i0} + \frac{1 - r_i^{\beta}}{1 - r_i} r_i^{\alpha-\beta-1} d_{i0} - \frac{1 - r_i^{\alpha}}{1 - r_i} u_{i0} \right],$$

where β = average decomposition period for the forest type.

3.1.2.3. *Period beyond the biological rotation*. The period after the new vegetation reaches biological maturity will have the same terms for prompt release and annual decomposition, but the uptake is modified due to the fact that as new crop reaches maturity, we assume that its CO_2 uptake is in equilibrium with release. The equation given below provides an approximate forecast of net emissions at any given year.

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} r_i^{\alpha-1} R_{i0} + \frac{1-r^{\beta_i}}{1-r_i} r_i^{\alpha-\beta-1} d_{i0} - \frac{1-r_i^{\alpha}}{1-r_i} u_{io} r_i^{\alpha-\gamma-\delta},$$

where γ = the biological rotation age of the subsequent forest and δ = the fallow period before regeneration.

In all the three cases represented above, if $r = 1$, then the model becomes the same as the base-year scenario due to the divergent geometric series in the neighborhood of unity. In this case, we use ϵ (a very small number) instead of p to compute the net emissions.

4. CONCLUSION

In this paper we have discussed the problems associated with the existing estimates of carbon stock, emissions and sequestration in tropical forests. We then present a description of a spreadsheet model—COPATH—intended for use in assisting researchers in various countries to undertake consistent estimates for their countries. The model is simplified in many respects so as to allow for a wide application in countries where the users may not necessarily be experts in forestry and global climate change. The first part of the model is used for estimating carbon stocks, emissions and sequestration for a given base year, and the second portion is useful in forecasting future emissions and uptake under various land-use scenarios. The choice of the most likely scenario will provide an estimate of the carbon flux profile of the country's forest sector given a set of land-use and forest utilization policies.

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